



NACA

RESEARCH MEMORANDUM

EFFECTS OF INLET WALL CONTOUR ON THE PRESSURE RECOVERY
OF A 10° 10-INCH-INLET-DIAMETER CONICAL DIFFUSER

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NATIONAL ADVISORY COMMITTEE
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Page 9, line 3: Change "radius ratio of 5" to "radius ratio of 8 "

Page 29, figure 15: Change values in key opposite triangle and square
(Δ and $\square$) from " $R/r = 5$ " to " $R/r = 8$."

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SUMMARY

An investigation was made of the influence on diffuser flow and performance characteristics of sharpness of curvature of the junction between the walls of a conical diffuser and a cylindrical approach tube. The work was done with a 10° 10-inch-inlet-diameter conical diffuser of 2:1 area ratio. The divergence angle was chosen small enough to avoid forced separation at the diffuser inlet. These investigations were made for two thicknesses of inlet boundary layer over a Reynolds number range, based on inlet diameter, of 1.2×10^6 to 3.2×10^6 and a mean inlet Mach number range of approximately 0.28 to choking. The inlet junction was formed as a circular arc, tangent to both the inlet cylinder and diffuser cone. The radius of this arc was varied over a range from practically zero to a maximum of 40 inches.

The static-pressure recovery of the diffuser was entirely independent of the radius of curvature of the inlet junction. No systematic variation of the exit velocity profiles with radius of arc was observed. A slight increase in limiting mass flow, which was more pronounced in the case of the thinner inlet boundary layer, was observed as the radius of the arc replacing the sharp inlet juncture was increased. The usual reduction in static-pressure recovery associated with thickening the inlet boundary layer was present.

INTRODUCTION

The fact that the aerodynamic performance of a diffuser is dictated in large measure by the growth and separation of the boundary layer on the diffuser walls is generally accepted. The development of the boundary layer in turn is known to be a function of the pressure gradient and is strongly influenced by severe gradients of rising static pressure.

Consideration of the flow at the junction of a conical diffuser with a cylindrical approach tube shows that a decrease in static pressure usually occurs as the junction is approached, followed by a related rise in static pressure leaving the junction. The intensity of this effect is related to the sharpness of curvature of the junction, the angle of divergence of the diffuser wall from the flow axis, and the thickness of the boundary layer. The presence of this disturbance increases the intensity of the gradient of rising pressure near the diffuser inlet and thus depresses the inlet-junction pressure below that corresponding to one-dimensional flow.

As the junction is approached, the negative pressure gradient in this region exerts a favorable influence on boundary-layer development. It has not been apparent to what extent this influence would compensate for the unfavorable effect of the associated intensification of the adverse pressure gradient immediately downstream of the junction. Excessive sharpness of the inlet juncture has usually been regarded as detrimental to diffuser performance. There appear to have been, however, no systematic investigations in which juncture shape was the sole variable.

To examine the problem, a series of measurements was made with a conical diffuser faired into a cylindrical approach tube with circular arcs ranging in radius from as near to zero as possible up to as large as necessary to establish performance trends clearly. The diffuser used was a 10° cone with a 10-inch-diameter inlet, having an area ratio of 2:1. This angle was chosen to obtain the strongest possible effects without encountering separation at the inlet. The tests were run from a mean inlet Mach number of 0.28 up to choking and a corresponding Reynolds number based on inlet diameter from 1.2×10^6 to 3.2×10^6 . The measurements were made for an inlet boundary layer having a displacement thickness of about 0.03 inch and also for one about five times as thick.

SYMBOLS

A	cross-sectional area of diffuser
H	total pressure
H_0	total reference pressure
M_i	mean inlet Mach number calculated from mass weighted total and static pressures obtained from surveys across diffuser inlet

p	static pressure
p_x	static pressure measured at a distance x inches from diffuser inlet
q_{c1}	inlet impact pressure
R	radius of arc at junction of diffuser walls and approach tube
r	radius of diffuser inlet
R/r	radius ratio
T_o	total temperature, degrees F
u	local velocity within boundary layer
U	local velocity at edge of boundary layer
u/U	velocity ratio for incompressible flow $\left(\sqrt{\frac{H_y - p_{wall}}{(H_y - p_{wall})_{max}}} \right)$
w	weight flow
y	vertical distance perpendicular to diffuser wall
Δp	static-pressure rise in diffuser measured at wall $(p_e - p_i)$
$\Delta p / \Delta p_{ideal}$	diffuser effectiveness
$\Delta H / q_{c1}$	loss coefficient
δ	boundary-layer thickness at $\frac{u}{U} = 0.95$
δ'	distance from surface beyond which contribution to integrals of δ^* and θ is negligible
δ^*	boundary-layer displacement thickness for two-dimensional incompressible flow $\left(\int_0^{\delta'} \left(1 - \frac{u}{U} \right) dy \right)$

θ boundary-layer momentum thickness for two-dimensional incompressible flow $\left(\int_0^{\delta'} \frac{u}{U} \left(1 - \frac{u}{U} \right) dy \right)$

δ^*/θ shape factor for two-dimensional incompressible flow

Subscripts:

i diffuser inlet conditions measured at duct wall

y vertical distance perpendicular to diffuser wall

APPARATUS

The test apparatus, as shown in figure 1, consists of an entrance bell, conical diffuser, and tail pipe. The entrance bell has a contraction ratio of 4:1. The diffuser consists of a straight inlet section, 6 inches long and 10 inches in diameter, and a 10° diverging cone, 23.6 inches long. The exit diameter is 14.14 inches, which gives the diffuser an expansion ratio of 2:1. A cylindrical tail pipe 28 inches long discharging into the atmosphere follows the diffuser. Thickening of the inlet boundary layer was accomplished by the insertion of a straight pipe 59 inches long between the bell and the diffuser inlet.

All sections, with the exception of the diffuser proper, were formed from $\frac{1}{2}$ -inch cold-rolled steel. All steel sections, with the exception of the tail pipe, were machined, painted, and sanded. The diffuser was constructed of mahogany. The inner surface was hand-finished and coated with clear lacquer. Photographs of the thinner-inlet-boundary-layer and thicker-inlet-boundary-layer configurations are shown in figures 2 and 3, respectively.

Five diffuser configurations were tested, each with two thicknesses of inlet boundary layer. The first configuration consisted of a 6-inch inlet and a 10° cone with a sharp juncture as shown in figure 1. The four succeeding shapes were made with circular cuts tangent to the straight inlet and the diverging section. The radii of the cuts were 5, 10, 20, and 40 inches, respectively.

Static-pressure orifices, 0.040 inch in diameter, were installed in the inlet bell, 59-inch-inlet section, and the tail pipe. Sixty static-pressure orifices at various distances from the inlet were inserted along a generatrix of the diffuser. The orifices were spaced $1/2$ inch apart in the first 4 inches of the approach tube. As the junction was reached

the spacing was decreased to 0.1 inch and remained so for 1 inch of the diverging section. The spacing was then gradually increased to a maximum of 3 inches in the vicinity of the diffuser exit.

Two centrifugal blowers in series supplied air at a maximum rate of 22,000 cubic feet per minute to the test setup.

Stagnation temperatures and pressures were recorded upstream of the inlet bell. Total temperatures were measured with an iron-constantan thermocouple and a potentiometer. Total pressures were measured with a shielded total-pressure tube. All pressure measurements were made with multitube manometers and recorded photographically.

Total-pressure measurements across the inlet and exit boundary layers were made with the rakes shown in figure 4. A static-pressure tube was mounted on each rake to record static pressures in the same plane as the total pressures were measured. The inlet-boundary-layer rake was mounted on a stainless-steel tube which ran longitudinally through the diffuser and was rigidly attached to a streamline strut fixed in the diffuser tail pipe. The exit boundary-layer rake was rigidly attached to the wall of the tail pipe and was in a position to survey the boundary layer at the junction of the diffuser exit and the tail pipe.

To insure turbulent inlet boundary layers, transition was fixed by gluing a 1-inch ring of cork particles in the inlet bell 12 inches upstream of the throat. The average diameter of the cork particles was approximately 0.10 inch.

METHOD OF ANALYSIS

Two-dimensional boundary-layer parameters were determined by incompressible methods similar to those used in reference 1. As in the case of reference 1, the majority of the profiles surveyed were in a region where the local Mach number was less than 0.70. At this speed the difference between the compressible and incompressible values of the boundary-layer shape factor was of the order of 5 percent. Two-dimensional values are used primarily as a measure of profile shapes since the bulk of existing data is presented in this form.

Curves of Reynolds number, based on inlet diameter, and mean inlet Mach number are shown in figure 5. The abscissa is presented as the ratio of the inlet static pressure measured at the wall of the diffuser to the reference total pressure H_0 .

The mass-flow calibration of the entrance bell and the 59-inch straight pipe was obtained from reference 1 since the same apparatus was used in each investigation.

The diffuser effectiveness $\Delta p/\Delta p_{\text{ideal}}$ is found by dividing the measured rise in static pressure in the diffuser by the rise in static pressure which would occur for the area ratio under consideration if the same quantity of flow was uniform and the diffusion isentropic.

RESULTS AND DISCUSSION

Radius Ratio

A plot of diffuser effectiveness against radius ratio is presented in figure 6. There appears to be no systematic variation of diffuser effectiveness with radius ratio for the two values of the boundary-layer thickness and speeds shown. The variations are greatest at low speeds, particularly in the case of the thinner inlet boundary layer, but they do not appear to be systematic in relation to R/r . In each of the four cases presented, a radius ratio of zero gave better results than a radius ratio of one. The quantity and accuracy of the data are not regarded as sufficient to draw any conclusions.

Static-Pressure Distribution

Longitudinal static-pressure distributions in the vicinity of the junction of the approach tube and cone are shown in figure 7. The sharp junction, which exists when the radius of the arc is practically zero, is located 6 inches from the diffuser inlet, as shown in figure 1. The ordinates of the curves are presented as the ratio of the static pressure measured along the wall of the diffuser to the reference total pressure H_0 and are not exact measures of the average Mach number which exists across the diffuser at any given distance from the inlet. The corresponding values of the reference total pressure are different for each curve. The majority of the curves show a depression in static pressure at the junction followed by a rise in static pressure, which decreases with increasing values of R/r , in the expanding section of the duct. The curves indicating a decrease in pressure ratio in the expanding region of the diffuser indicate a development of supersonic velocities. At a radius ratio of 8, a change in the trend of the static-pressure-distribution curves appears. For those flows which do not reach sonic velocity, little or no depression is present in the vicinity of the junction, particularly in the case of the thicker inlet boundary layer.

In figure 8 a representative set of static-pressure-distribution curves for the complete length of diffuser is presented for the thinner inlet-boundary-layer diffuser at $\frac{R}{r} = 1$.

The effect of radius ratio on the longitudinal static pressure distribution is best shown in figure 9. Representative curves at common values of inlet pressure ratio for the smallest and largest radii were obtained by interpolation of figure 7 and are presented for both thicknesses of inlet boundary layer. The large radius ratio has eliminated the depression in static pressure at the junction. However, the static-pressure curves again coincide approximately 1 inch downstream of the junction and continue in that condition throughout the remainder of the diffuser. Although a common value of inlet pressure ratio was used for both thicknesses of inlet boundary layer, the static-pressure depression in the case of the thicker inlet boundary layer for $\frac{R}{r} = 0$ is not as severe and the pressure increase downstream of the junction is not as great. The cushioning effect of the thicker inlet boundary layer reduced the intensity of the depression in static pressure for $\frac{R}{r} = 0$. However, the static-pressure rise in the diverging section of the diffuser, as, for example, at $x = 9$ inches from the inlet, was substantially less for the thicker inlet-boundary-layer diffuser. This is due to the greater boundary-layer displacement thickness reducing the effective expansion area of the conical section.

Velocity Profiles

Typical inlet and exit velocity profiles are presented in figures 10 and 11. The inlet velocity profiles of figure 10 show the characteristic tendency of the inlet-boundary-layer thickness to remain essentially constant with an increase in velocity. The addition of a cylindrical pipe approximately six diameters in length to the diffuser inlet resulted in the inlet displacement thickness being increased about five times. Exit boundary-layer thicknesses, figure 11, as well as the boundary-layer shape factor do not appear to follow any systematic trend as the radius ratio is varied. In most cases separation is imminent, particularly in the case of the thicker inlet boundary layer at high speeds.

Limiting Mass Flow

A plot of limiting mass flow against radius ratio is shown in figure 12. The ordinate is presented as the ratio of the limiting mass flow per unit area through the diffuser to that which would exist with uniform flow at a Mach number of 1. A slight increase in limiting mass flow with an increase in radius ratio is present for both configurations, with the increase being more pronounced in the case of the thinner-inlet-boundary-layer diffuser. In both configurations, an increase in

radius ratio shifted the effective throat of the diffuser upstream. As the radius ratio was increased, the position of the effective throat moved further upstream of the inlet survey station with the result that greater limiting mass flows were measured at the inlet due to the increased effective cross-sectional area. In the case of the thicker inlet boundary layer, however, the rate of change of effective inlet cross-sectional area was less than that of the thinner inlet boundary layer and resulted in smaller increases in limiting mass flows for corresponding increases in radius ratios.

Diffuser Effectiveness

In figure 13(a), the diffuser effectiveness has been plotted as the ordinate over the complete range of Mach numbers for both thicknesses of inlet boundary layer. A slight scatter is present, particularly at low Mach numbers, presumably due to flow fluctuations which were observed at the diffuser exit. The downward trend in pressure recovery with increasing Mach number, before choking is reached, has been observed before in diffusers of approximately the same included angle. The usual reduction in static-pressure recovery associated with increasing the inlet-boundary-layer thickness, when the boundary layer is substantially less than that for fully developed pipe flow, is present in the thicker inlet-boundary-layer configuration. Figure 13(b) is an enlargement of figure 13(a) in the vicinity of the choking Mach number for both configurations.

In figure 14, the pressure-recovery curves for a radius ratio of one are compared with a diffuser of similar radius ratio investigated in reference 1. In each case the same inlet bell and inlet pipe were used. However, the diffuser of reference 1 had an expansion angle of 12° as compared to 10° for the present configuration. In addition, a 9-inch straight section was built integral with the 12° diffuser whereas a 6-inch straight section was used with the 10° diffuser. The effect of shortening the straight section can be seen by the increase in choking Mach number for the 10° diffuser. Decreasing the expansion angle from 12° to 10° increased the pressure recovery through the diffuser, particularly at Mach numbers near choking.

Loss Coefficient

Although extensive exit surveys to obtain a precision evaluation of the loss coefficient were not done for this investigation, a rough qualitative effect of the curvature may be had by estimating the value of the total pressure loss. The measurements were obtained from boundary-layer surveys making the assumption that the total pressure at the survey station prevails over the entire circumference of the duct. Results of

such calculations are shown in figure 15. The curves would indicate that the total pressure losses in the case of the sharp corner are slightly higher than for a radius ratio of 5.

With due consideration of the limited amount of data on which these curves are based, it would appear that the total pressure loss, if influenced by the radius of curvature, would be in the direction of a slightly higher loss for the sharper corner.

CONCLUSIONS

An investigation was made with a 10° 10-inch-inlet-diameter conical diffuser of 2:1 area ratio to determine the influence on flow characteristics and pressure recovery of sharpness of curvature of the junction between the walls of a conical diffuser and a cylindrical approach tube. These investigations were made over a Reynolds number range, based on inlet diameter, of 1.2×10^6 to 3.2×10^6 and a mean inlet Mach number range of approximately 0.28 to choking. Two thicknesses of inlet boundary layer were used, one having a displacement thickness of about 0.03 inch and the other about five times as thick. Varying the inlet wall shape led to the following conclusions which are equally applicable for both thicknesses of inlet boundary layer. Data at two thicknesses only are not regarded as sufficient to draw any broad generalizations; however, they suggest the probability that the conclusions are independent of the inlet-boundary-layer thickness.

1. The over-all static-pressure recovery, expressed as the ratio of the actual rise in static pressure divided by the ideal rise in static pressure, was entirely independent of the inlet wall shape.

2. Below choking Mach numbers the static-pressure distribution in the diffuser was not affected by a change in radius ratio except in the region of the junction of the cylindrical approach tube and the conical section.

3. Modifying the contour of the diffuser inlet produced no systematic trend in exit profile shape.

4. A slight increase in limiting mass flow was observed as the radius of the inlet junction was increased.

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REFERENCE

1. Little, B. H., Jr., and Wilbur, Stafford W.: High-Subsonic Performance Characteristics and Boundary-Layer Investigations of a 12° 10-Inch-Inlet-Diameter Conical Diffuser. NACA RM L50C02a, 1950.

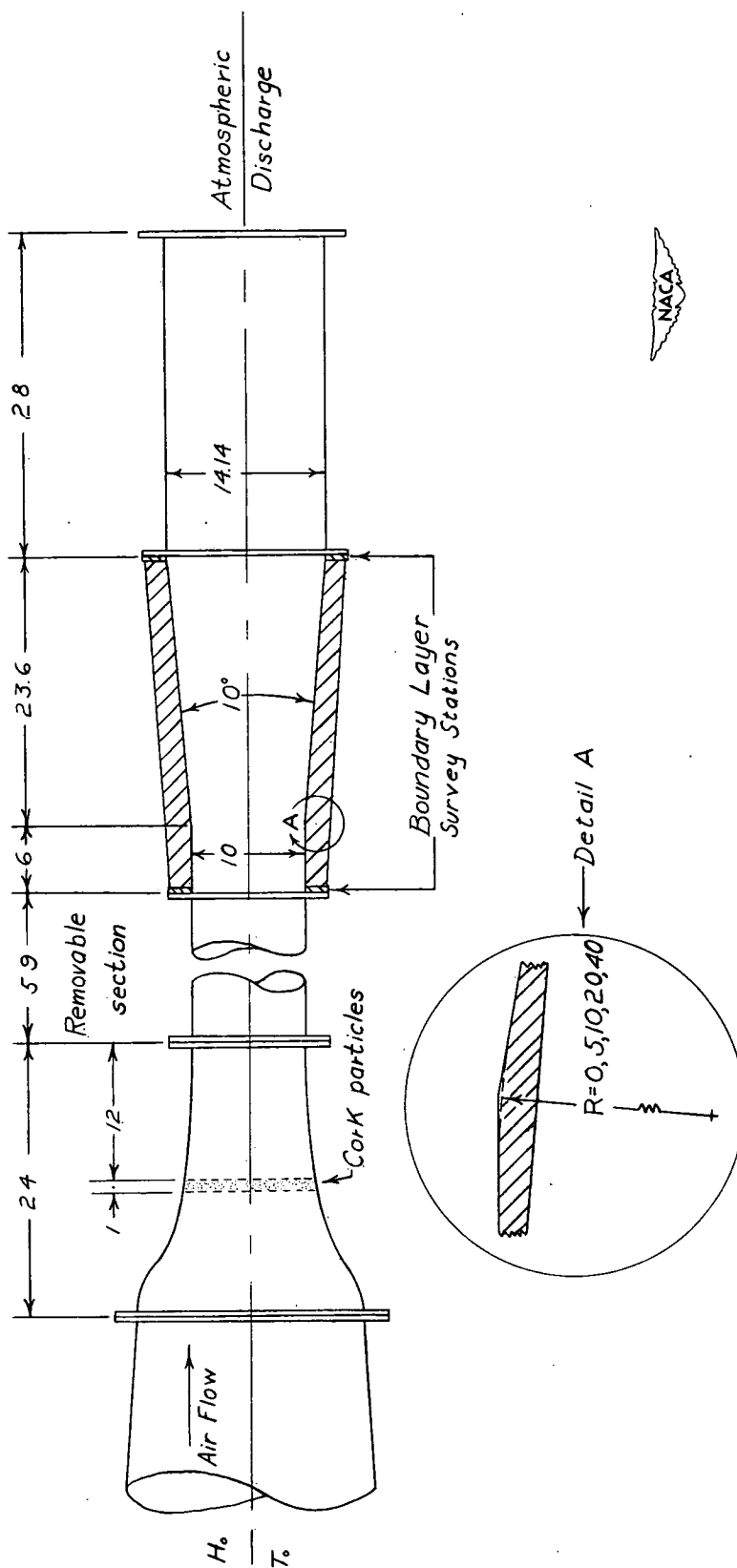


Figure 1.- Line drawing of apparatus. All dimensions are in inches.

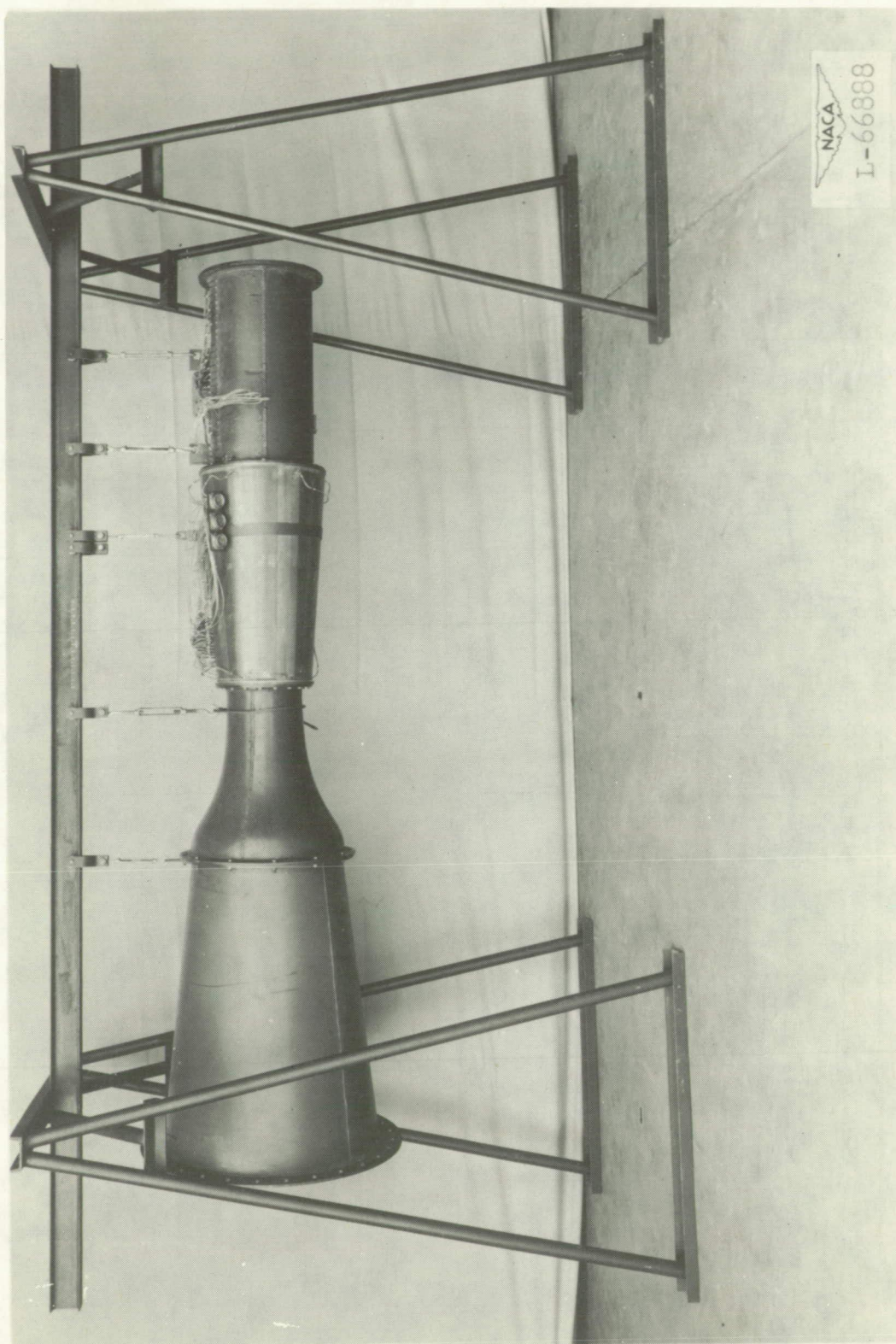


Figure 2.- Thinner-inlet-boundary-layer configuration.

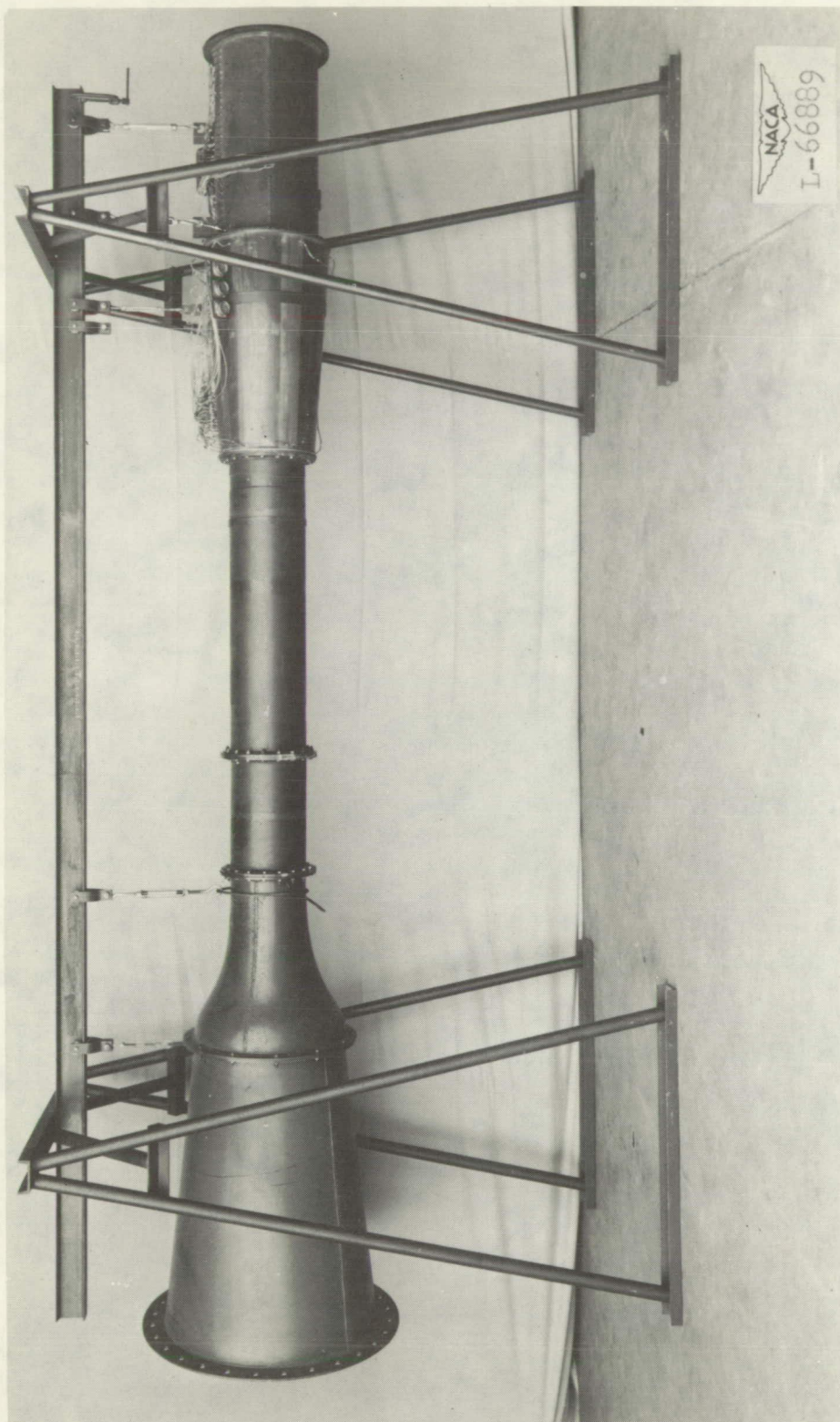
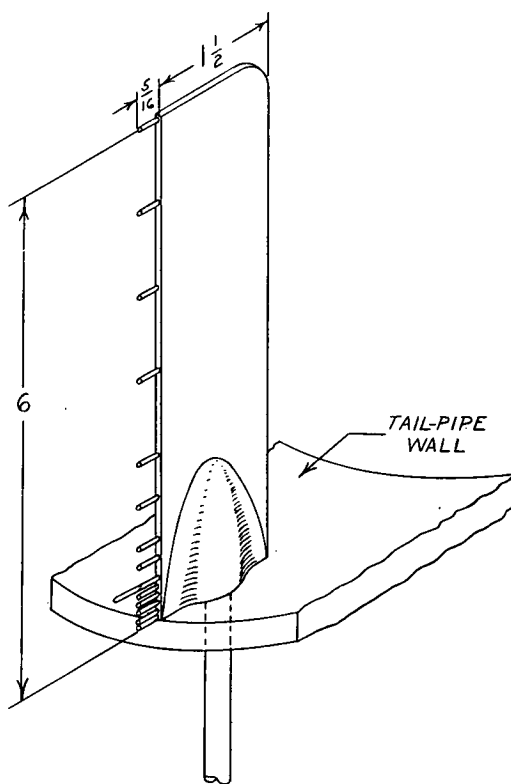
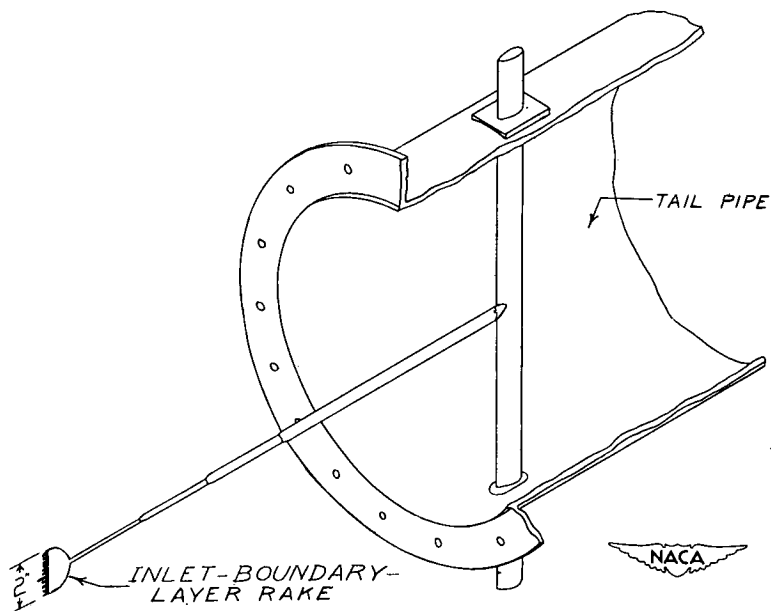


Figure 3.- Thicker-inlet-boundary-layer configuration.



(a) Exit-boundary-layer rake.



(b) Inlet-boundary-layer rake.

Figure 4.- Boundary-layer survey apparatus.

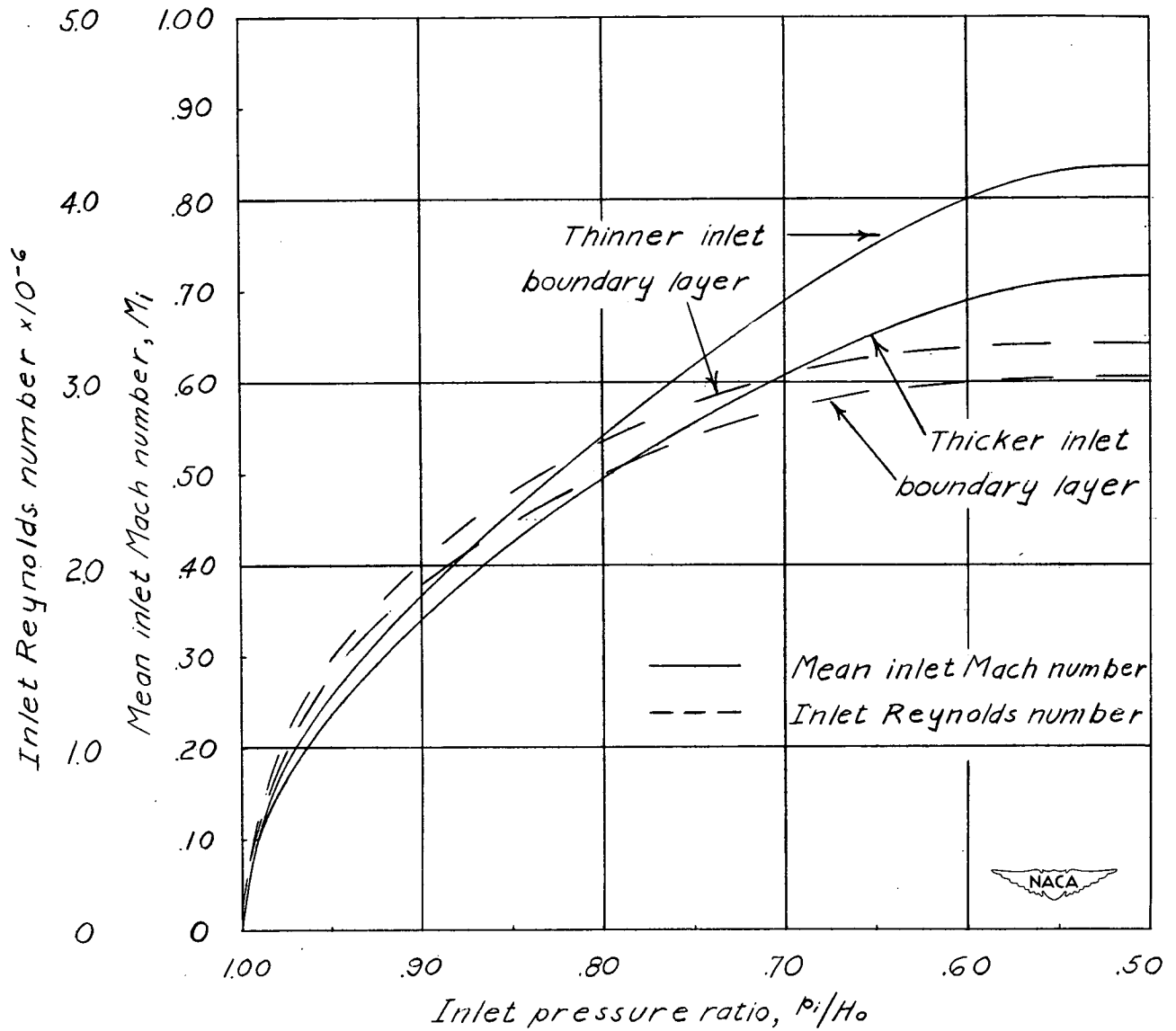
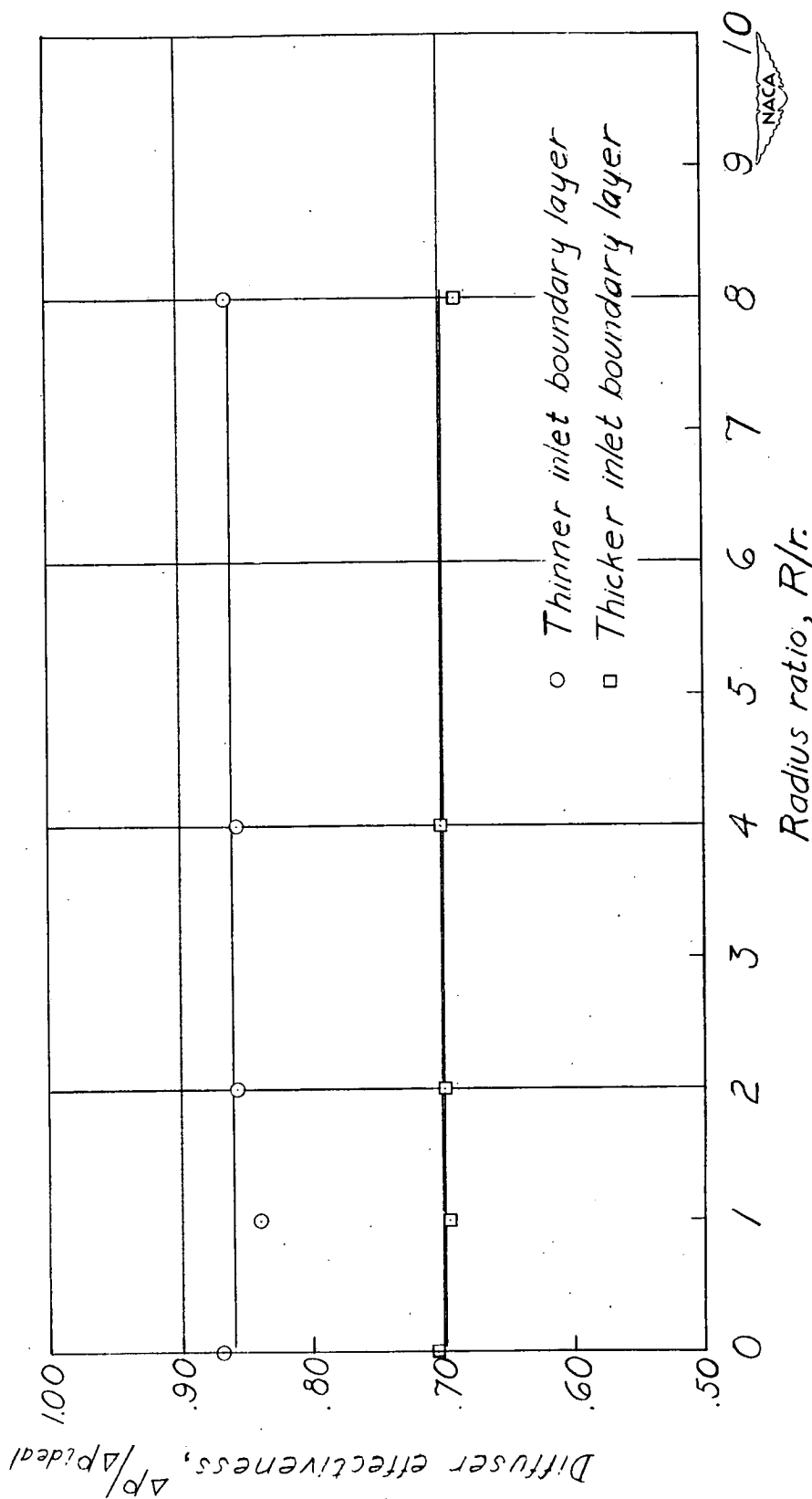
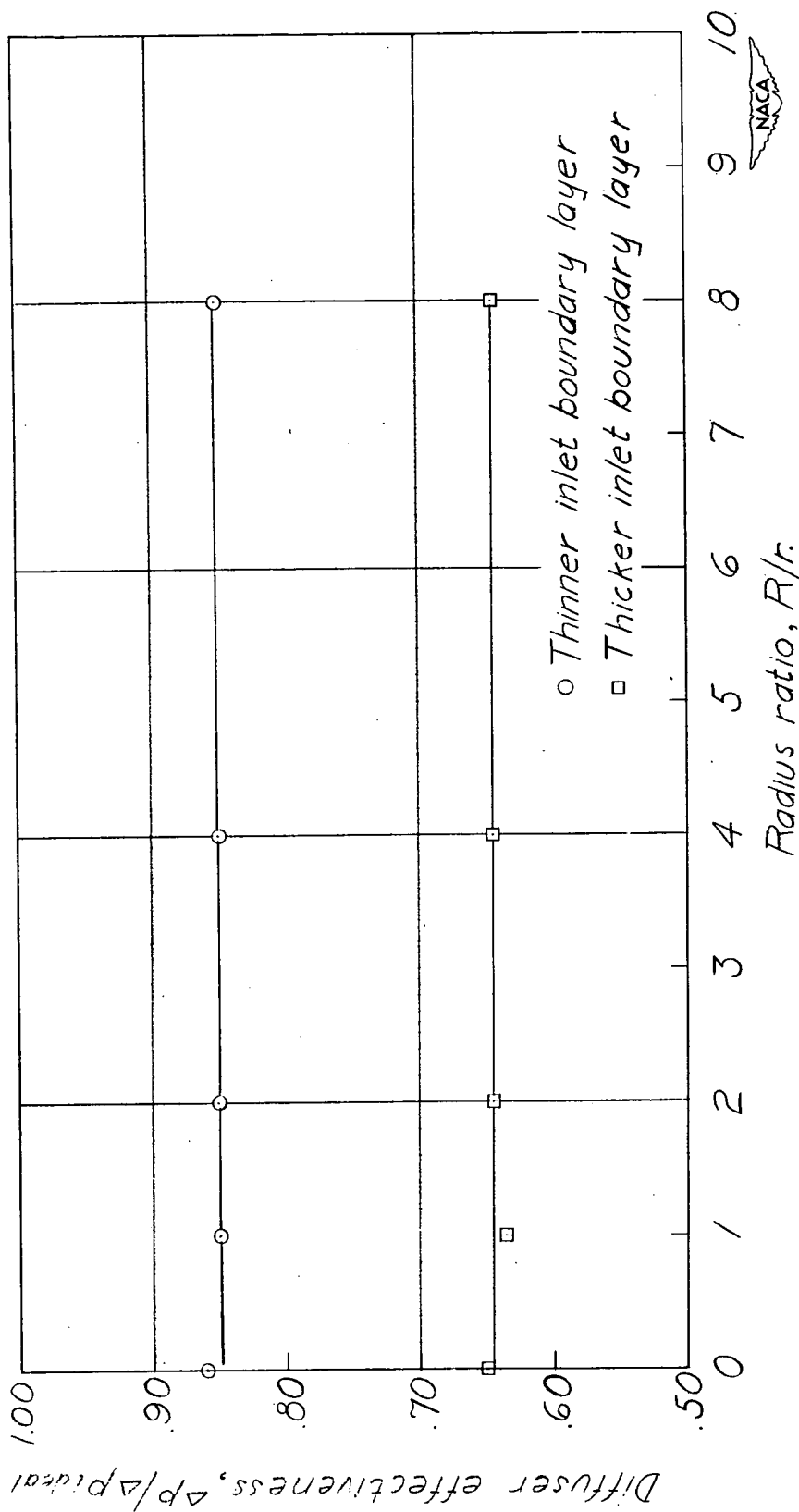


Figure 5.- Variation of mean inlet Mach number and inlet Reynolds number with inlet pressure ratio.



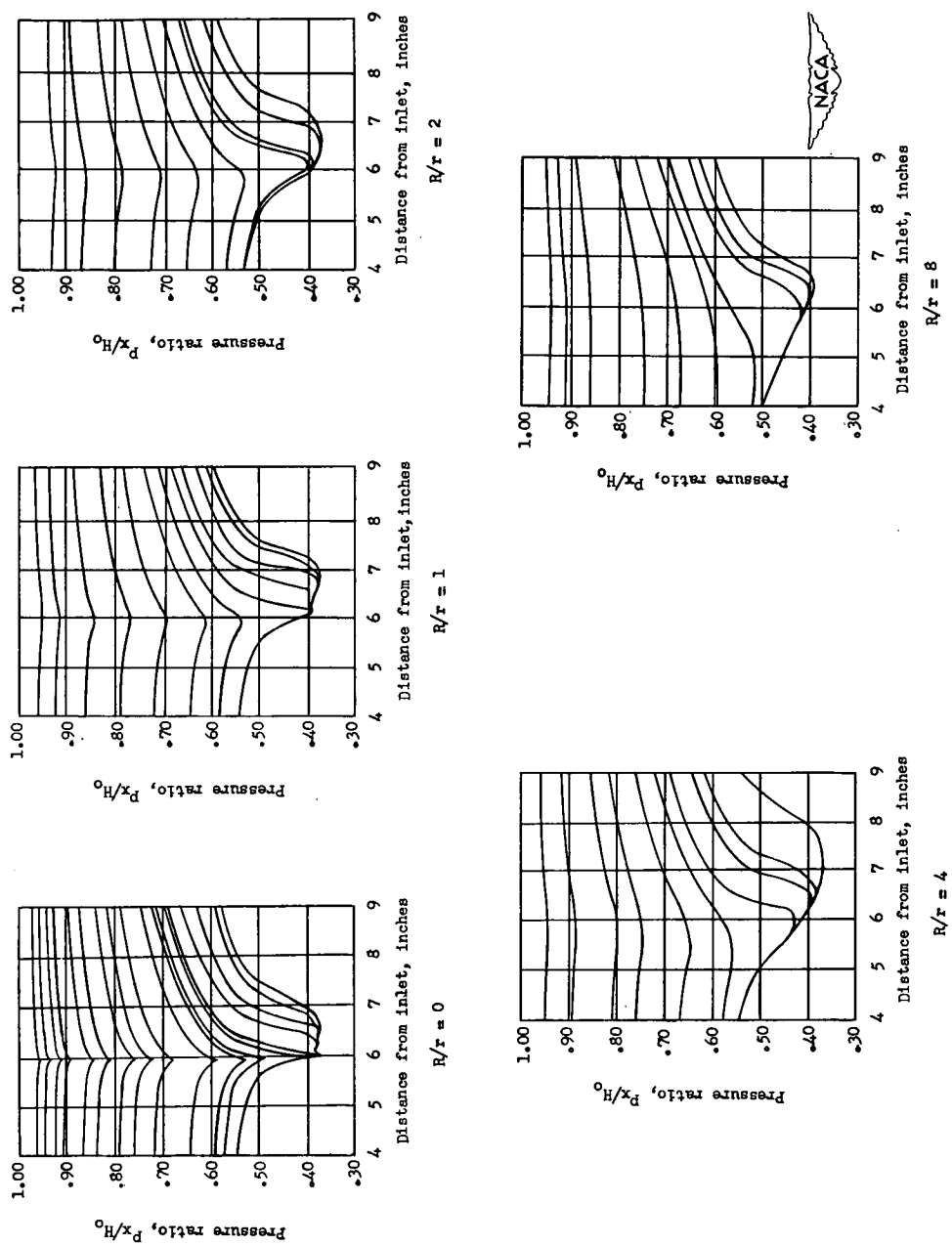
(a) $M_1 = 0.35$.

Figure 6.- Variation of pressure recovery with radius ratio.



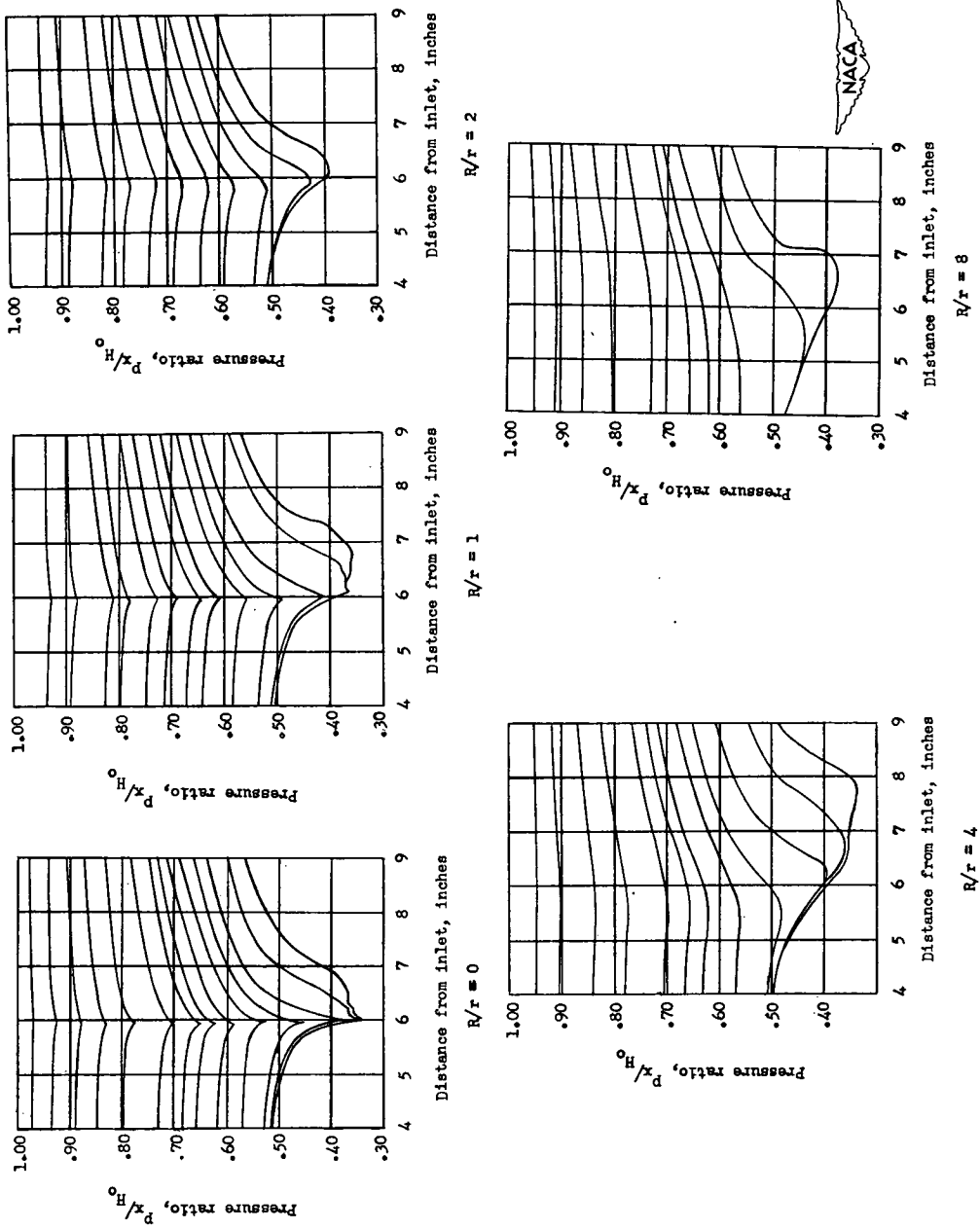
(b) $M_1 = 0.65$.

Figure 6.- Concluded.



(a) Thinner inlet boundary layer.

Figure 7.- Static-pressure distribution at the junction of the inlet pipe and diverging section.



(b) Thicker inlet boundary layer.

Figure 7.- Concluded.

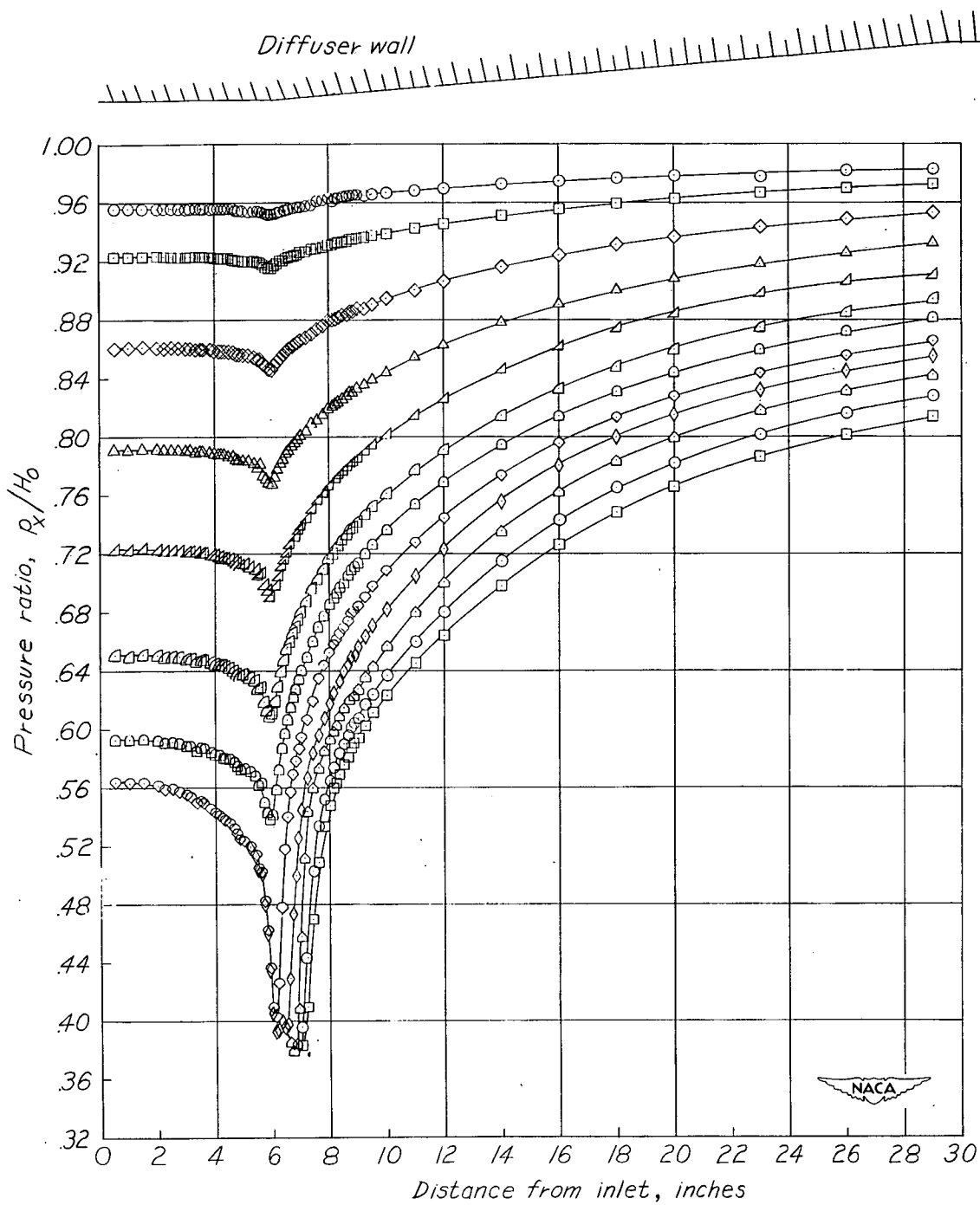


Figure 8.- Static-pressure distribution, thinner inlet boundary layer. $\frac{R}{r} = 1.0$.

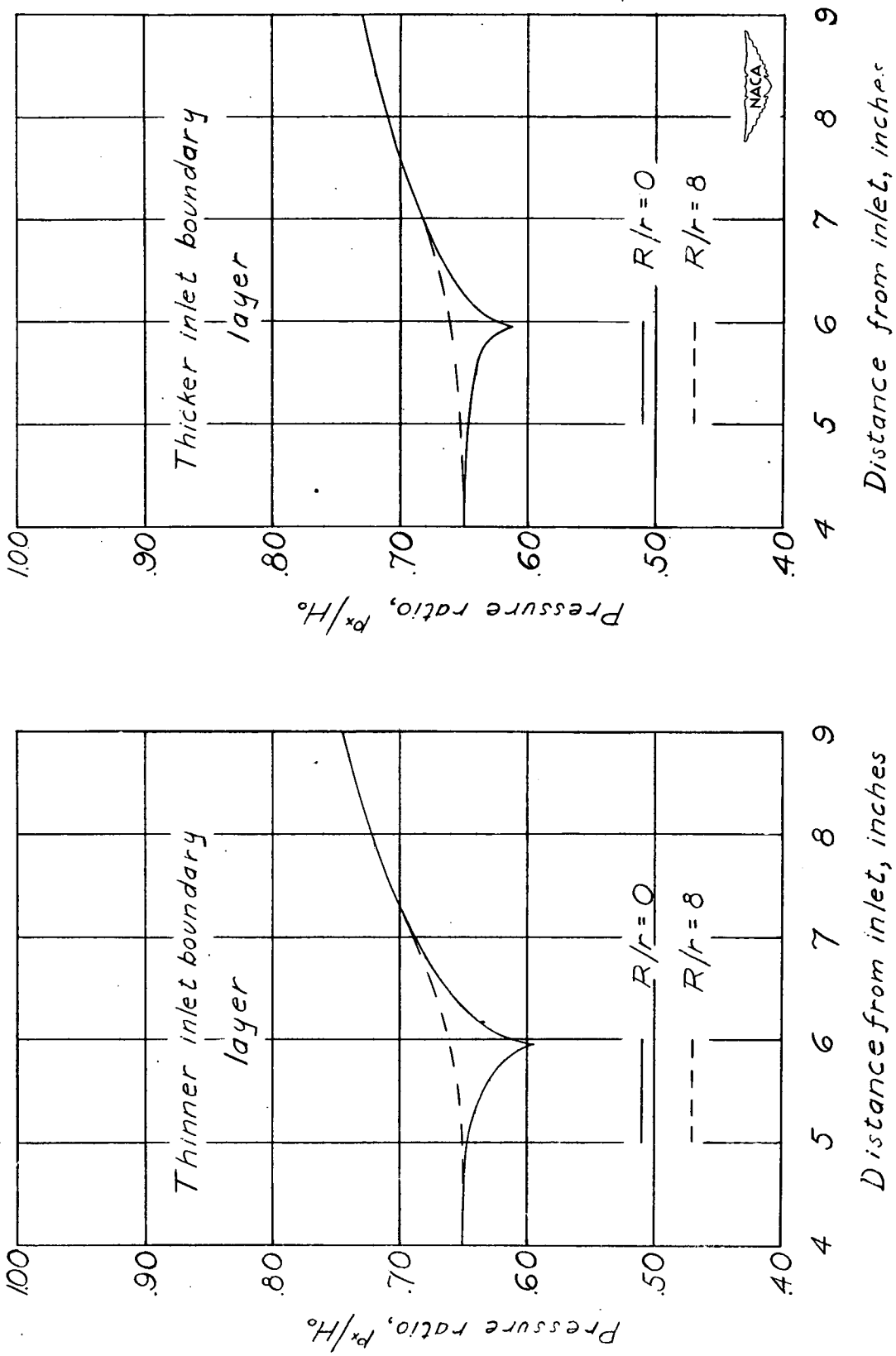
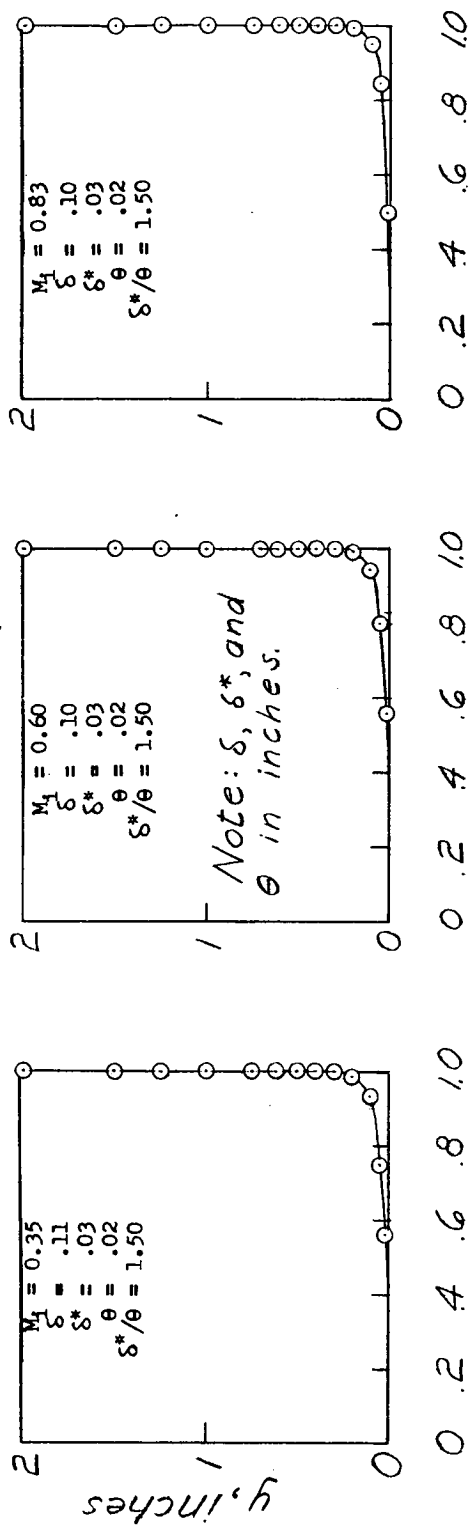


Figure 9.- Comparison of static-pressure distribution.

Thinner inlet boundary layer



Thicker inlet boundary layer

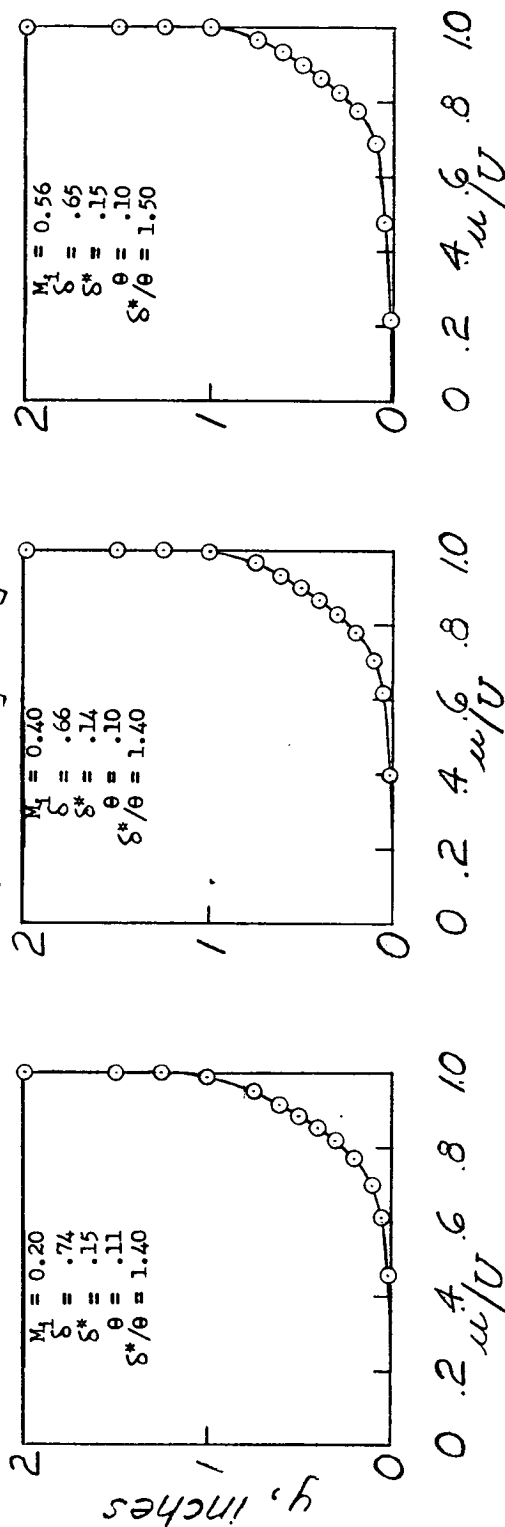
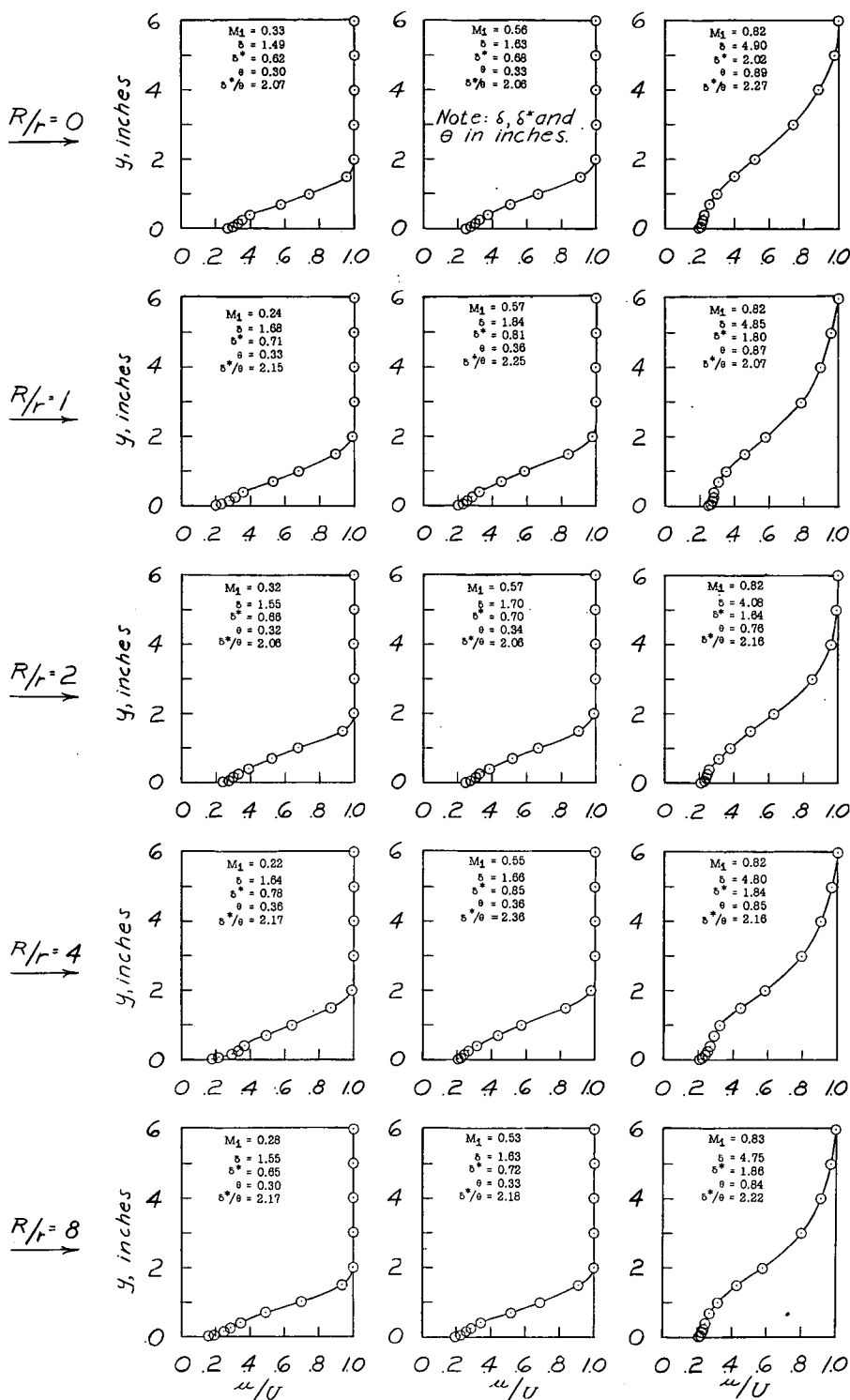


Figure 10.- Inlet boundary-layer profiles.

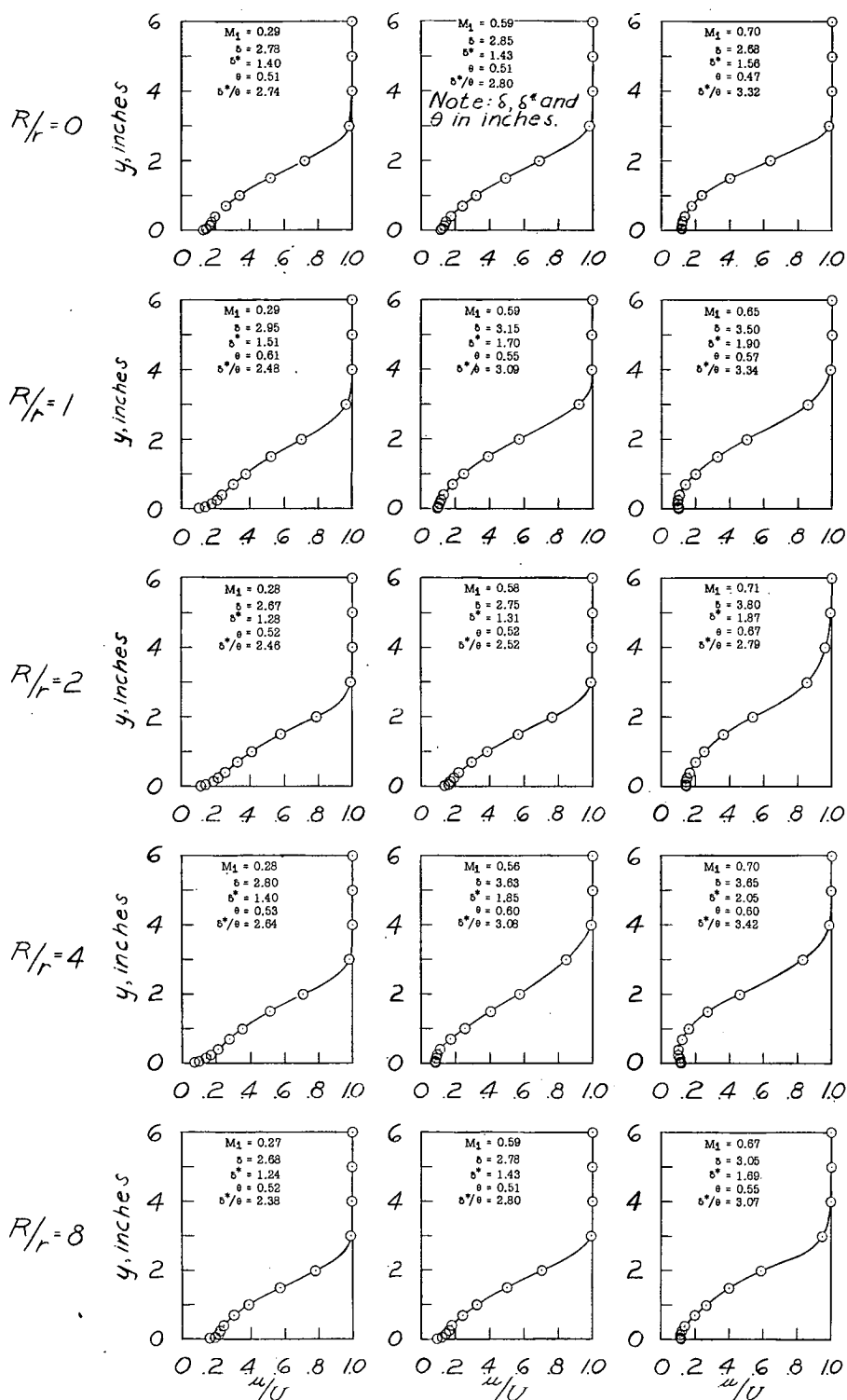




(a) Thinner inlet boundary layer.



Figure 11.- Exit velocity profiles.



(b) Thicker inlet boundary layer.



Figure 11.- Concluded.

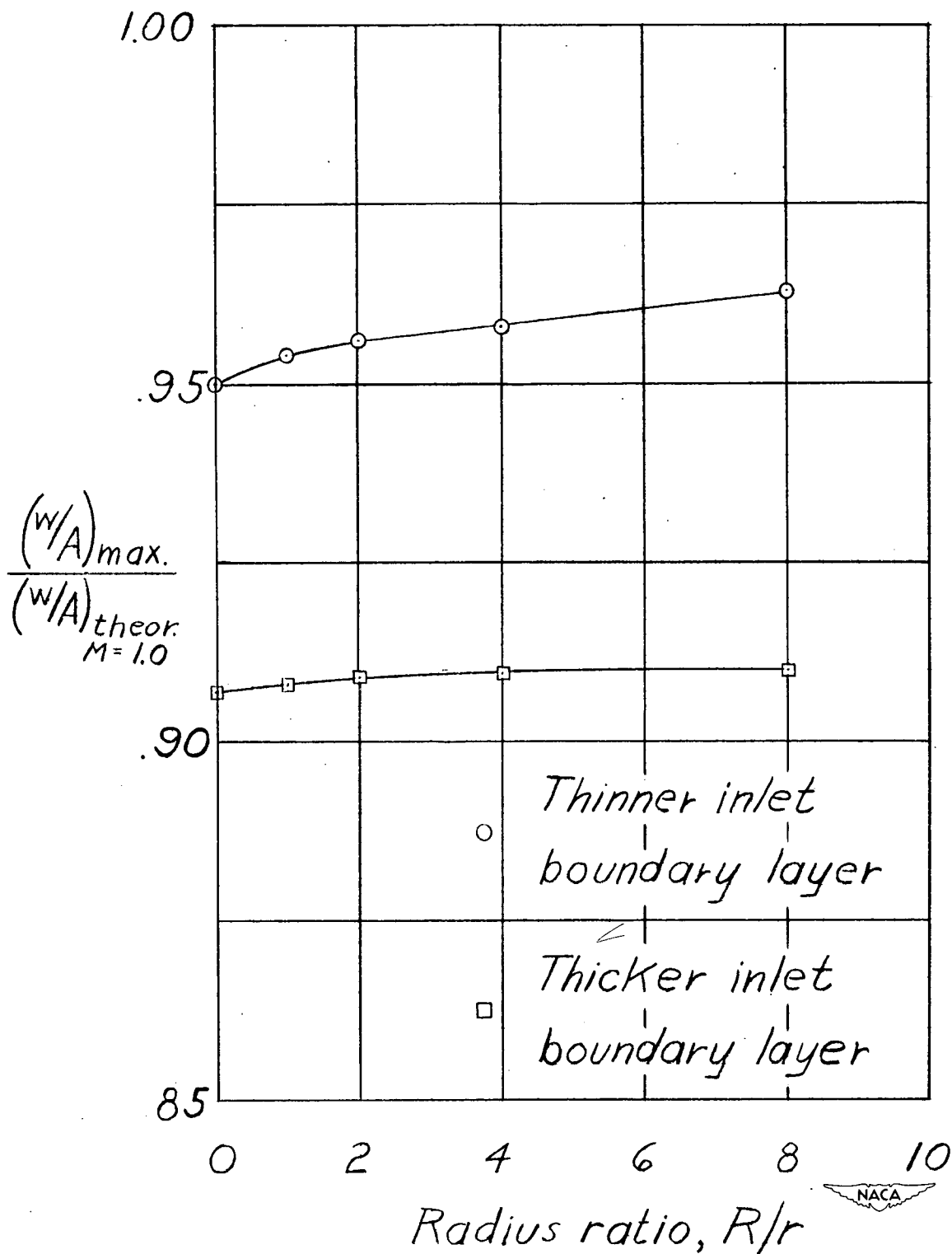


Figure 12.- Variation of maximum weight flow with radius ratio.

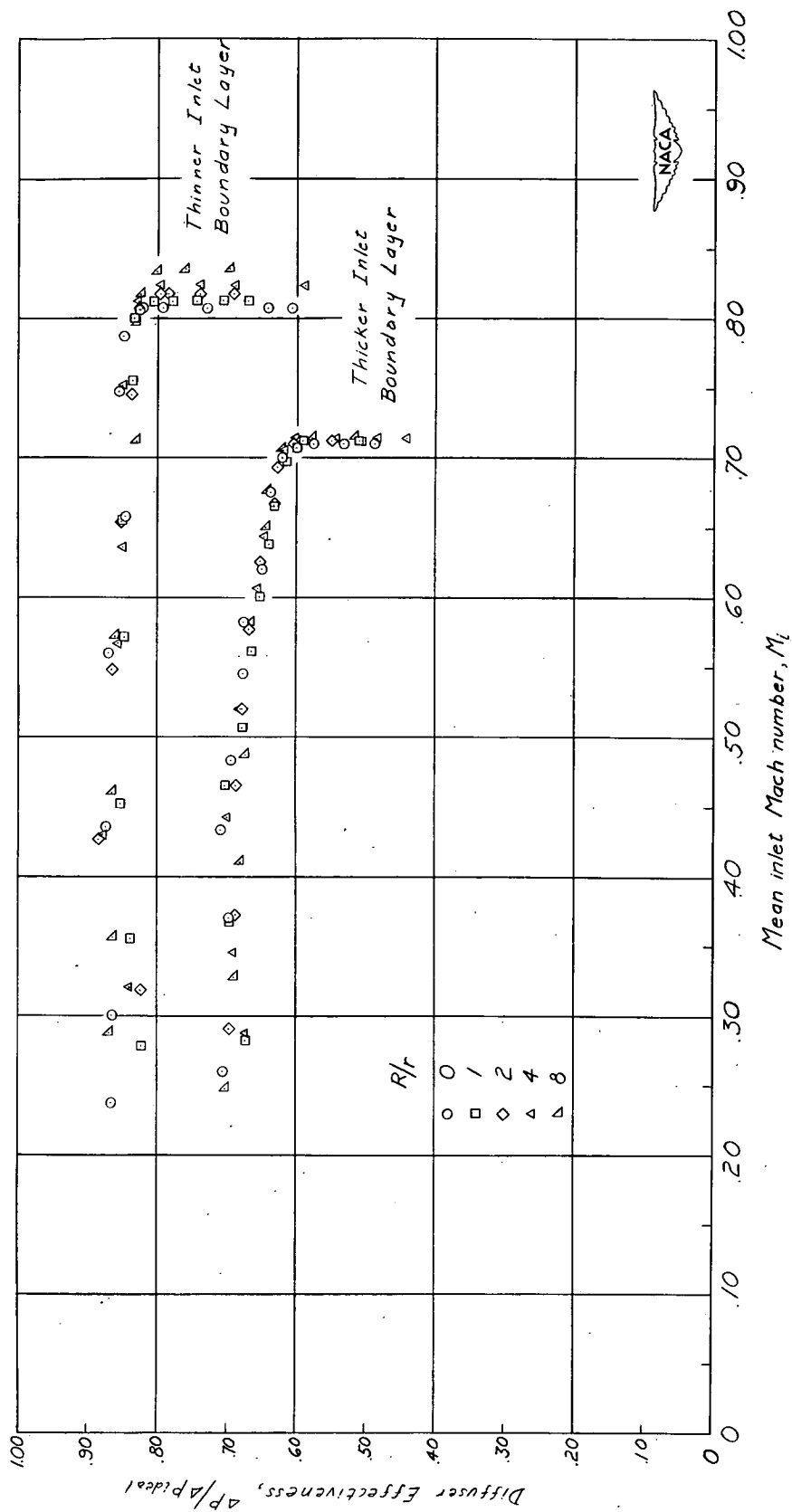


Figure 13.- Variation of diffuser effectiveness with mean inlet Mach number.

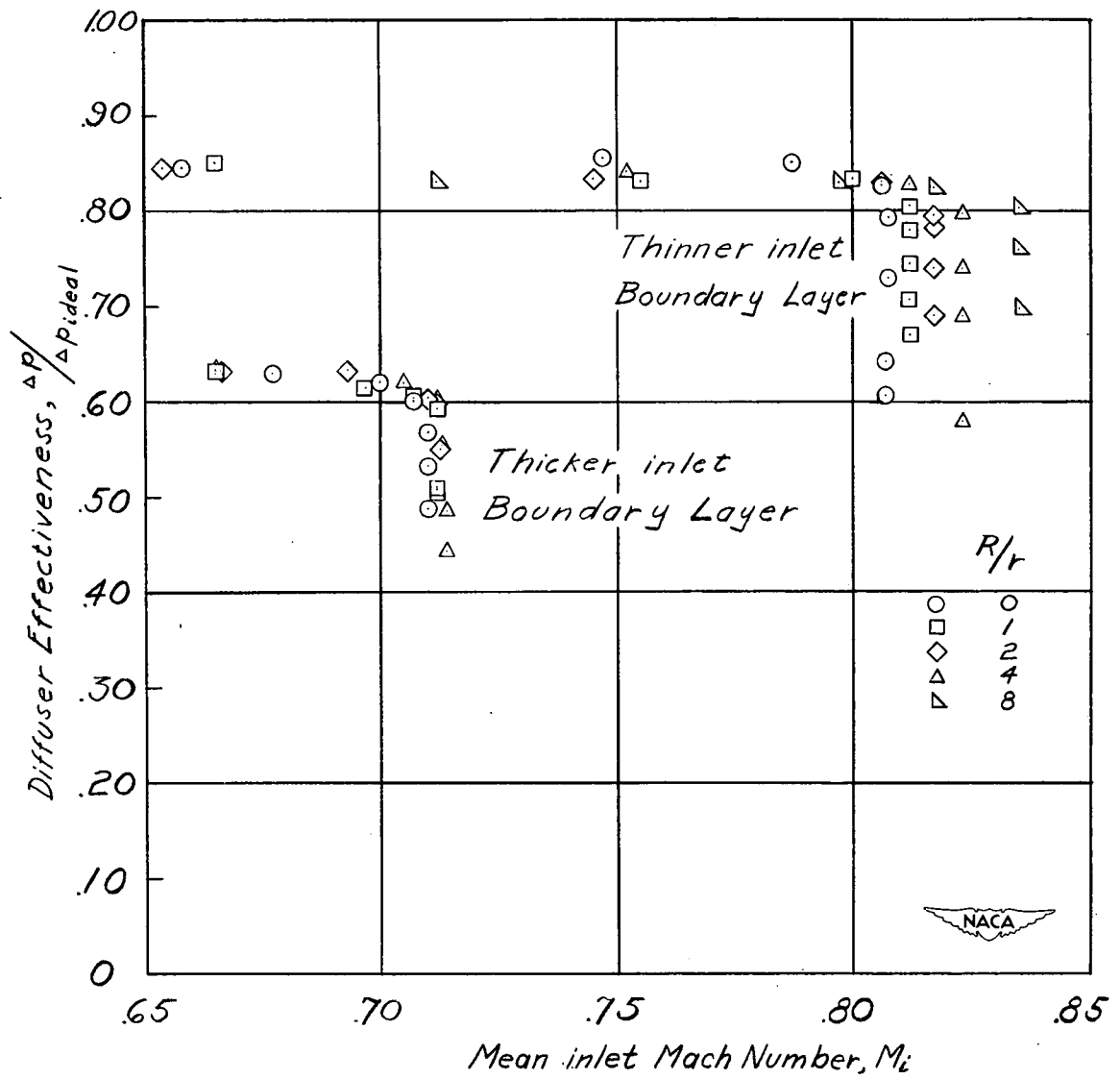


Figure 13.- Concluded.

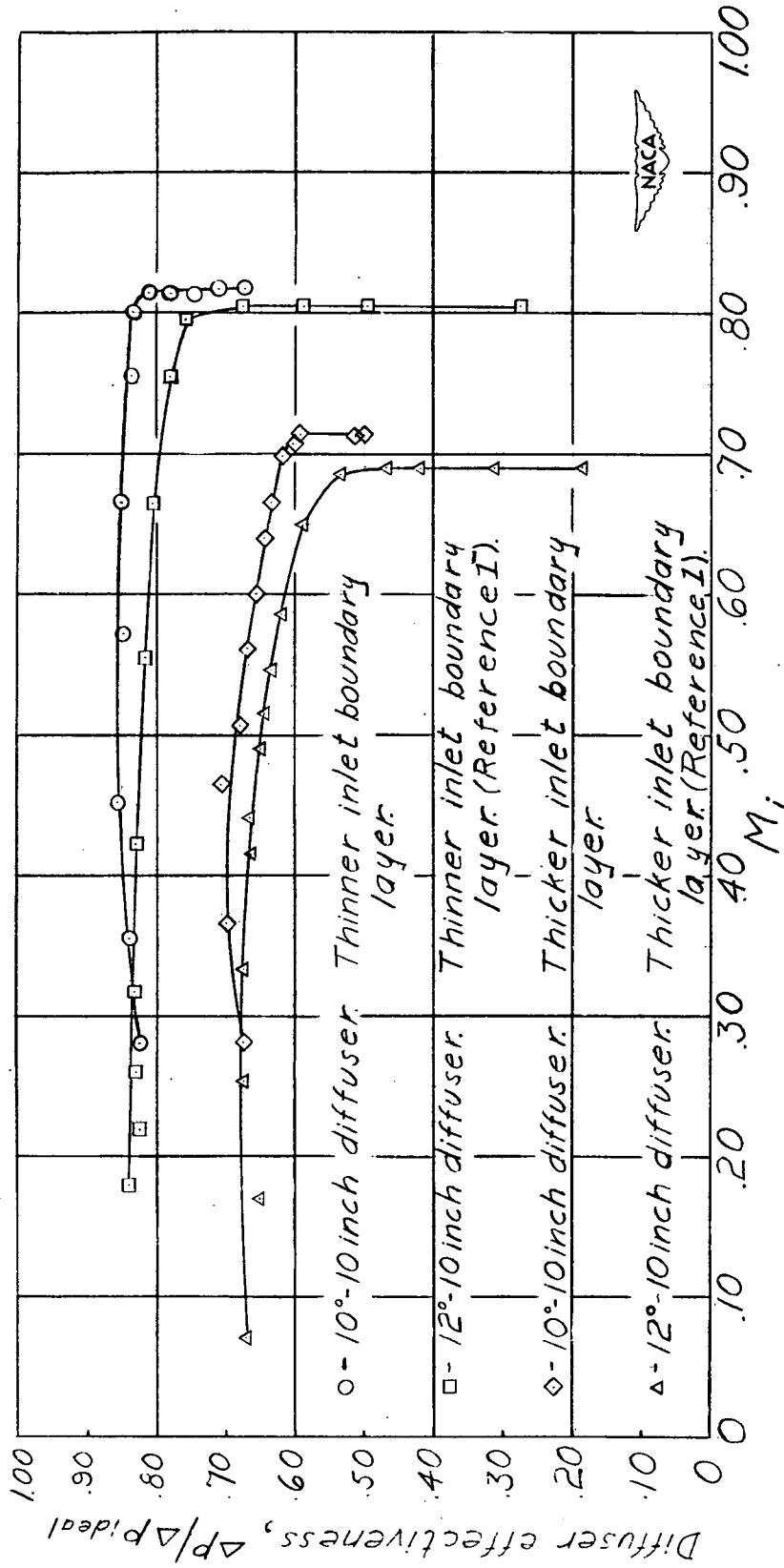


Figure 14.- Variation of diffuser effectiveness with mean inlet Mach number. $\frac{R}{r} = 1$.

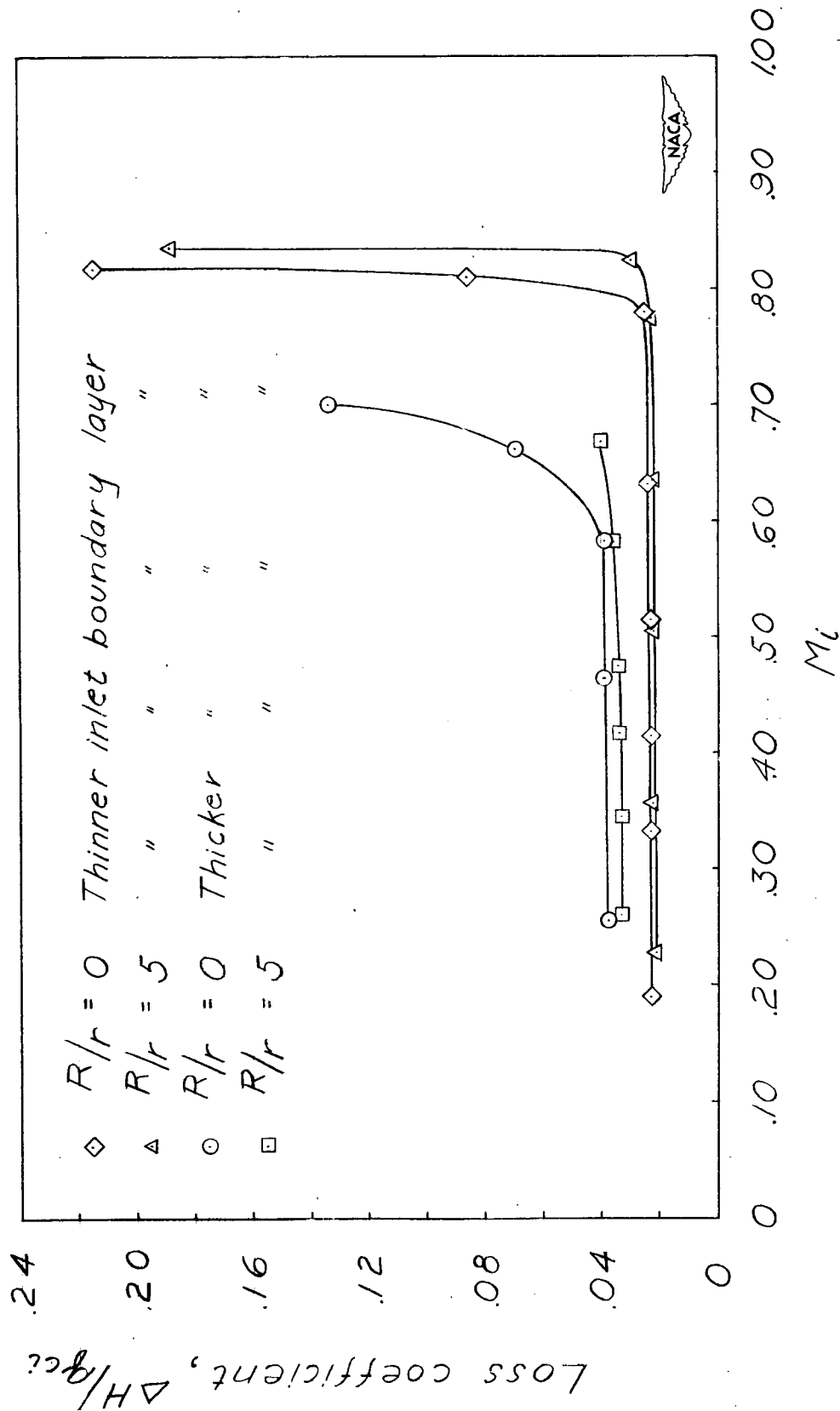


Figure 15.- Variation of loss coefficient with mean inlet Mach number.